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Human Response to Ductless Personalized Ventilation with Local Air Cleaning: Air Quality and Prevalence of SBS Symptoms

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Abstract

The impact of local air cleaning and cooling of the head region by ductless personalized ventilation (DPV) on perceived air quality (PAQ) and Sick Building Syndrome (SBS) symptoms was studied. Thirty subjects participated in experiments performed in a test room with displacement ventilation (DV) and six workstations, three of which had DPV. The DV kept air temperature in the occupied zone (1.1 m above the floor). Pollution load was simulated by PVC floor covering and the bioeffluents generated by the subjects (60% recirculated room air). DPV sucked the air distributed over the floor by the DV and supplied it to the breathing zone of the subjects. The subjects were allowed to control the position of the DPV supply diffuser and the personalized flow rate. Each subject participated in five 4-hour experiments: 23 °C with DV only, 23 °C with DPV with air filter, 29 °C with DV only, 29 °C with DPV with air filter and 29 °C with DPV without filter. During the experiments the subjects simulated office work and answered on computerized questionnaires. At warm environment PAQ and air freshness significantly improved when DPV was used. Eye dryness increased significantly with time but was not influenced by air temperature and filtering. At 29 °C the facially applied air movement from DPV increased the eye dryness. The SBS symptoms increased with time and were higher (not significantly) at the warm conditions. Air movement did not have profound impact on the SBS symptoms, while filtering had only at 23 °C.

Keywords – ductless personalised ventilation; air cleaning; local cooling; air quality; SBS symptoms

1. Introduction

Providing building occupants with thermal comfort and clean air for breathing is important for their health and performance. Present total volume ventilation systems are inefficient because clean and cool air is supplied far from the occupants and is mixed with the warm and polluted room air when it reaches the occupants. Personalized ventilation aims at providing clean and cool air directly to the breathing zone of occupants [1]. Its positive effects on

occupants' health, comfort and performance has been documented [2]. Numerous designs of desk incorporated personalized ventilation ducted with central HVAC system has been proposed and studied. Ductless personalized ventilation (DPV) combined with displacement ventilation (DV) has been also introduced [3, 4]. DPV sucks the cool and clean air spread over the floor by displacement air distribution and supplies it to the breathing zone of each occupant.

Recent study [5] reported that acceptability of PAQ and freshness of the air improved when facially air movement was applied. The elevated air movement diminished the negative impact of increased air temperature, relative humidity and pollution level on PAQ. The degree of improvement depended on the pollution level, the temperature and the humidity of the room air. At low humidity level of 30% an increased velocity could compensate for the decrease in perceived air quality due to an elevated temperature ranging from 20 °C to 26 °C. In a room with 26 °C, increased air movement was also able to compensate for an increase in humidity from 30 % to 60 %. The elevated velocity of recirculated polluted room air did not decrease the intensity of SBS symptoms, but movement of clean, cool and dry air did so. It was also reported that using personalized ventilation supplying clean and cool air at warm environment significantly improves PAQ and thermal comfort, decreases the intensity of SBS symptoms to those prevailing in a comfortable room environment without personalized ventilation and improves self-estimated and objectively measured performance [6].

The positive effect of DPV on peoples' thermal comfort and PAQ at warm environment has been documented [7]. However the impact of DPV combined with DV on SBS symptoms and performance is not known. Due to the fact that DPV may not always suck the clean air supplied by displacement ventilation and in some cases it may be mixed with room air, the use of local air cleaning at each workstation may be beneficial. It was reported in [8] that the PAQ was better when DPV with active carbon filter was used compared to the case of DPV without filter. However the effect of using filter on SBS symptoms and performance is not known.

Comprehensive experiments were performed to study the physiological and subjective response of people at comfortable and high room air temperature when using DPV supplying filtered and unfiltered polluted room air. Large database comprising SBS symptoms, eye symptoms (blink frequency, tear film stability, eye irritation), comfort (PAQ and thermal comfort) and performance was collected and analyzed. This paper reports on the impact of facially applied elevated air movement and air filtering on SBS symptoms.

2. Method

A human subject experiment was carried out in a climate chamber (6.4 x 4.8 x 6.0 m³) with displacement ventilation (DV). The chamber was located in a tall hall with temperature controlled as in the chamber. There were six workstations in the chamber consisting of a desk and a laptop PC. All workstations were at approximately equal distance from the air supply diffuser. Four of the desks had DPV systems consisted of a fan, two flexible silencers and a movable arm with a round movable panel as a supply diffuser (described in [9]). Depending on the tested conditions, DPV systems were equipped either with Filter 1 (1,1 kg of activated carbon type CKV-3) or with Filter 2 (250 g of 8% KMnO₄ impregnated activated alumina; 230 g of BPL4x10) or did not have a filter. The DPV at maximum could provide 16 l/s of personalized flow and the intake height was limited to 10 cm above the floor.

Experimental Conditions

Thirty subjects (17 males and 13 females) participated in the experiment. The subjects were recruited among university students. They were exposed to five experimental conditions comprising: 23 °C and DV only, 23 °C and DPV with Filter 2, 29 °C and DV only, 29 °C and DPV, and 29 °C and DPV with Filter 1. The room set point temperature was achieved at 1.1 m above the floor. DV supplied 135 l/s at temperature 5 °C lower than the room set point temperature. Recirculation was used during the entire experiment with constant ratio (60 % re-circulated air and 40 % outdoor air). Relative humidity of supplied air was not controlled but room air relative humidity was measured in the range 30-40%. In order to simulate pollution load the floor was covered with one year old linoleum. Other pollution sources included bio effluents from human subjects and the desks with computers.

Physiological measurements

Samples of tear mucus were taken in order to study tear film stability. Subjects' face was recorded during the whole exposure by web-cameras placed on every workstation. The records were analyzed to define eye blink rate. Face temperature was measured several times during the exposures. The physiological measurements are not reported in this paper. Results on eye symptoms (blink rate and tear film stability) are reported in [10].

Subjective measurements

During the experimental sessions, computerized questionnaires were used to collect data regarding subjects' response to the environment. The subjects assessed PAQ using an acceptability scale divided in two parts, from "clearly unacceptable" (coded as -1) to "just unacceptable" (-0.01) and from "just acceptable" (0.01) to "clearly acceptable" (1), odour intensity, irritation

in nose, throat and eyes, thermal sensation and comfort for the whole body and locally for body parts, acceptability of the air movement, preference for air movement and description of their clothing.

The SBS symptoms assessment (performed on continuous scale) included questions on dryness of nose/throat/eyes (not dry - overwhelming dry), headache (no headache – severe headache), thinking ability (difficult to think – head clear), ability to concentrate (difficult to concentrate – easy to concentrate), wellbeing (feeling bad – feeling good), fatigue (tired – rested).

Performance measurements

The performance measurements included subjective measurements (self-assessed performance) and objective measurements based on speed and accuracy of solving different tasks (multiplication, Sudoku game, etc.). These data are reported in a separate paper.

Experimental procedure

The subjects were divided into five groups of six people each. In five experimental sessions the subjects were exposed randomly to the five experimental conditions. Each experimental session took four hours and consisted of several parts.

Right after arrival, participants entered the tall hall and were asked to fill in paper questionnaire about PAQ and face temperature measurements were taken. Subjects adjusted their clothing to feel thermally comfortable and entered the chamber. Before the subjects took their place, while standing, they filled in again a paper questionnaire regarding the PAQ. After that each subject sat at the workstation with his/her name and ID already displayed on the computer screen. Then the acclimatization part started and subjects were exposed in the chamber for approximately 20 min in order to adapt to environmental conditions. This time was used to build-up the pollution in the chamber. During the acclimatization, subjects were not allowed to use the DPV systems. At the end of the acclimatization period tear film sampling and skin temperature measurements were taken. Then subjects were asked to stand up and fill in paper questionnaires about PAQ and overall thermal sensation (TC). Then the subjects left the chamber and entered the tall hall, where they filled in paper questionnaire (PAQ) and then rested for 5 min.

The subjects enter the chamber again. They first filled in paper PAQ questionnaire while standing and then each of them took their place at the designated workstations. Subjects who had DPV started the device and were asked to adjust the position of the RMP and the supply air flow rate to their preferences. The subjects responded on questions on PAQ, thermal sensation and SBS symptoms. Then the performance tasks began and continued to the end of the experiment with 10-min break in between when subjects could go to the restroom. The subjects responded to the SBS symptoms questions approximately every 40 min from the beginning of the performance tasks to the end of the experiment.

At the end of the exposure, when subjects finished completing questionnaires and tasks, the face skin temperature was measured. Then tear film was sampled (the subjects who had DPV were asked to turn it off before the sampling). After the tear film sampling, subjects were asked to stand up and to assess PAQ (on paper form questionnaire). Finally, they left the chamber, entered the tall hall and filled in the last PAQ questionnaire (paper form). During the experiments subject were encouraged to modify their clothing in order to feel comfortable.

Data analyses

The Shapiro–Wilk’s W-test was used to test the normality of the distribution. For data with a normal distribution, ANOVA (repeated measures analysis of variance) was used and, for more detailed results, the Newman–Keul test was performed. Data not normally distributed were analyzed using the nonparametric Friedman ANOVA and Wilcoxon matched pair tests. A chi-squared test was used for the nominal data.

3. Results

As already discussed subjects assessed PAQ several times during the exposure. The reported PAQ changed during the acclimatization part of the experiment, when subjects moved in and out from the climate chamber. However after that PAQ remained almost unchanged in time to the end of the experiment. There was a significant difference ($p < 0.02$) between conditions at 23 °C and conditions at 29 °C. The higher air temperature influenced negatively the PAQ. The PAQ at “29 °C and DV only” was significantly ($p < 0.01$) lower than at “29 °C and DPV” and “29 °C and DPV with Filter 1” meaning that local air movement influenced positively the perceived air quality at 29 °C. However, no significant difference was found between the two conditions at 23 °C, which indicates that local air movement improved PAQ only at high temperatures. There was also no significant difference between the conditions “29 °C with DPV” and “29 °C with DPV with Filter 1”.

In order to quantify the acceptability of the perceived air quality, the percentage of dissatisfied with PAQ averaged for the whole exposure (excluding the acclimatization period) was calculated. The results are shown in Figure 1. It can be seen that at 29 °C, the local air movement clearly has a positive impact on PAQ while the percentage of dissatisfied is the same for both conditions at 23 °C (acceptability of PAQ was already very high at “23 °C with DV only”). There is a difference between the conditions without DPV, namely “23 °C with DV only” and “29 °C with DV only”, confirming the impact of temperature on PAQ. However, no impact of local air filtration was found. There is no difference in the percentage of dissatisfied with or without local air filtration at 29 °C.

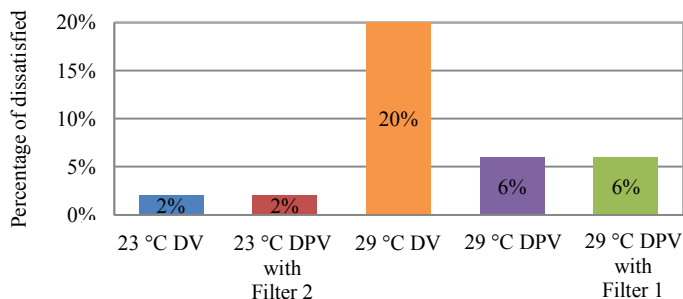


Fig. 1 Percentage of dissatisfied with PAQ averaged for the whole exposure (excluding the acclimatization period) under all experimental conditions

The results showed clearly that the highest air freshness was reported when subjects were exposed to the conditions at room air temperature of 23 °C. No significant difference was found between the conditions with DV only and DPV equipped with Filter 2 at the air temperature of 23 °C. The air freshness decreased as air temperature increased. As expected, at 29 °C the air freshness with DV only was significantly ($p<0.01$) lower than for the conditions at 23 °C. The results in Figure 2 show that using the DPV with or without Filter 1 at 29 °C did not improve the air freshness to the same level as in conditions at 23 °C. The difference between the two conditions at 23 °C and all the conditions at 29 °C was significant ($p<0.01$). The increased personalized air velocity at 29 °C provided significantly ($p<0.04$) higher air freshness than that at the corresponding condition without DPV. However, no significant difference was found between the two conditions at 29 °C with DPV. This may imply that used activated carbon filter (Filter 1) combined with DPV did not influence the perception of the air freshness.

Median values of eye dryness for all subjects for the five experimental conditions are shown in Figure 3. The results show that the dryness of eyes reported by subjects varies with time. The eye dryness increased significantly ($p<0.05$) between the beginning and the end of exposure for all conditions except for the condition at “29 °C with DV only”. At the end of exposure eye dryness at the condition “29 °C with DV only” was significantly ($p<0.02$) lower than in the conditions at 29 °C with DPV. However, at the low temperature of 23 °C no difference at the end of the exposure was found with and without use of DPV. The results suggest an increase of eye dryness due to the applied local air movement at high air temperature level. Eye dryness was not significantly different at the end of exposure between 23 °C and 29 °C without elevated air movement, i.e. without DPV. This means that in case of long exposure air temperature in the range of 23-29 °C did not have an impact on self-reported dryness of eyes.

At the end of exposure eye dryness was not significantly different between the conditions “29 °C with DPV” and “29 °C with DPV with Filter 1” and between the conditions “23 °C with DPV with Filter 2” and “23 °C with DV only”. The result suggests that local filtering of room air did not have impact on eye dryness.

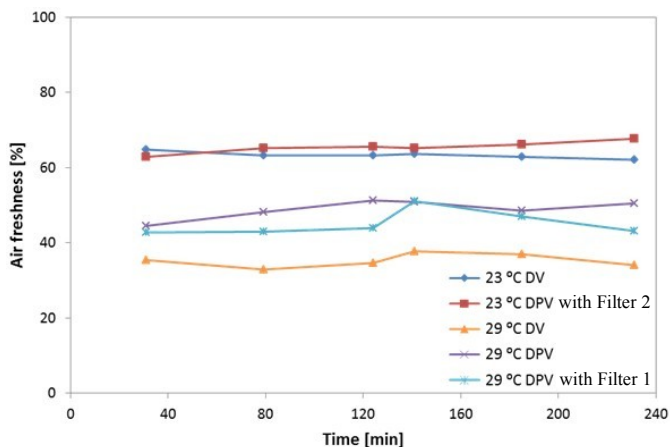


Fig. 2 Air freshness averaged for all subjects under the five experimental conditions

The nose and throat dryness was less affected by the studied conditions than the dryness of eyes. It decreased as air temperature decreased. At the end of exposure dryness was significantly ($p < 0.04$) higher at 29 °C than at 23 °C. No significant effects of local air movement or local air filtration on dryness was found although the results at 29 °C showed slightly higher dryness under the conditions with air movement.

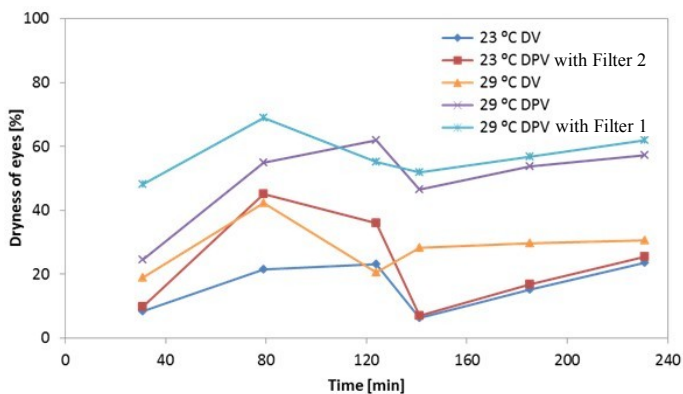


Fig. 3 Median values of eye dryness for all subjects under the five experimental conditions

Headache, ability to think, well-being, fatigue and arousal change during the exposure. Compared to the beginning of the exposure the severity of headache increased (significantly; $p < 0.02$), difficulty of thinking increased (significantly; $p < 0.01$), well-being decreased (significantly; $p < 0.01$), fatigue increased (significantly; $p < 0.001$) at the end of all five experimental conditions. Figure 4 shows how difficulty to think developed with time under all five exposures. At the end of the exposure headache, difficulty to think, difficulty to concentrate and fatigue were significantly ($p < 0.03$) lowest while well-being and arousal level significantly ($p < 0.05$) highest under the condition “23 °C and DPV with Filter 2” compare to the other conditions. Only the reported well-being was not significantly different for the conditions at 23 °C, i.e. it was not influenced by use of DPV with Filter 2.

It was easiest for the subjects to think clearly, to concentrate and well-being and arousal were higher and fatigue lower at room temperature of 23 °C than 29 °C. However the differences were not significant.

At the end of exposure no significant differences were found in reported headache, difficulty to think, well-being, fatigue and arousal between conditions with DPV and corresponding conditions without DPV, neither there were significant differences between the conditions with and without Filter 1 at 29 °C.

In order to account for the possible differences at the beginning of the exposure the SBS data were further analyzed in the following way: the difference between first and last response was calculated for each subject under all conditions. These differences were used to calculate median values of the SBS symptoms for all subjects. The analyses of the results confirmed that air temperature did not have impact on the SBS symptoms neither had air movement and filtering at 29 °C.

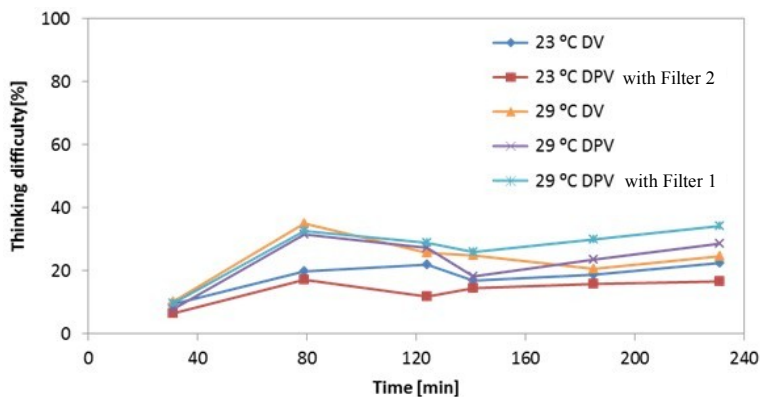


Fig. 4 Median values of ability to think for all subjects under the five experimental conditions

4. Discussion

The results of the present study confirm previous findings [5] that increase of air temperature affects negatively PAQ while elevated facially applied air movement improves PAQ and air freshness, especially at warm environment. The results reveal that use of Filter 1 (active carbon) for cleaning room air polluted by floor covering and bioeffluents did not improve PAQ. The cleaning effect may have been small compare to the effect of the elevated air movement. This result contradicts with the finding in [8] that DPV coupled with active carbon filter significantly improve PAQ. One of the reasons may be the exposure time. Present paper presents analyses of results obtained at the end of 4-hour exposure while in [8] on much shorter exposure (15 min). The positive effect of filtering room air on PAQ may have been rather small compared to the effect of elevated air movement and may have diminished in time. Indeed, detailed analyses of the PAQ data obtained in this study revealed that at the beginning of exposure presence of active carbon filter (Filter 1) improved PAQ. However, as suggested above, this improvement dissolve in time due to the stronger effect of air movement on PAQ. Present results also confirmed previous findings [5] that the positive effect of elevated air movement on PAQ decreases with the decrease of the temperature. Filtering of the room air at 23 °C did not improve PAQ.

The exposure time had negative impact on eye dryness, headache, ability to think, well-being, fatigue and arousal. After long exposure no impact of room temperature in the range 23-29 °C on self-reported dryness was found. Local filtering of the polluted room air at 23 °C with Filter 2 and with Filter 1 at 29 °C also did not have impact on eye dryness. However at high room air temperature the facially applied air movement by the DPV increased the eye dryness. The combined effect of air temperature, relative humidity, cleanliness and movement on eye dryness needs to be studied.

Present results support previously documented negative effect of increased air temperature on the SBS symptoms. It was easier for the subjects to think clearly, to concentrate and well-being and arousal were higher and fatigue lower at room temperature of 23 °C than 29 °C. However the differences were not significant. The impact of the pollution may have been much stronger than the impact of the air temperature. Previous findings that elevated movement of polluted room air does not have positive effect on SBS symptoms but clean air does [5, 6] was also confirmed. The use of active carbon filter (Filter 1) did not decrease the SBS symptoms. Importantly present results revealed that use of Filter 2 at 23 °C improved the SBS symptoms. The positive effect of Filter 2 at warm environment remains to be studied. The use of DPV in practice may be attractive (both

with mixing and displacement ventilation) when efficient methods for filtering the room air are used. This will greatly improve occupants' health, comfort and performance and may lead to energy savings.

5. Conclusions

At warm environment PAQ and air freshness significantly improved when DPV was used. Eye dryness increased significantly with time but was not influenced by air temperature and air cleaning. At 29 °C the facially applied air movement from the DPV increased the eye dryness. The SBS symptoms increased with time and were higher (not significantly) at the warm conditions. Air movement generated by the DPV did not have profound impact on the SBS symptoms. The use of local cleaning of the polluted air decreased the SBS symptoms at 23 °C.

6. Acknowledgment

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